

Alpha-particle clustering in excited expanding self-conjugate nuclei

B. BORDERIE¹, AD. R. RADUTA^{1,2}, G. ADEMARD¹, M. F. RIVET¹,
E. DE FILIPPO³, E. GERACI³, N. LE NEINDRE^{1,4}, G. CARDELLA³,
G. LANZALONE⁵, I. LOMBARDO⁵, O. LOPEZ⁴, C. MAIOLINO⁵,
A. PAGANO³, S. PIRRONE³, G. POLITI³, F. RIZZO^{5,3} and
P. RUSSOTTO^{5,3}

¹ Institut de Physique Nucléaire, CNRS/IN2P3, Université Paris-Sud 11,
91406 Orsay, France

² National Institute for Physics and Nuclear Engineering,
Bucharest-Magurele, Romania

³ INFN, Sezione di Catania and Dipartimento di Fisica e Astronomia,
Università di Catania, Italy

⁴ LPC, CNRS/IN2P3, Ensicaen, Université de Caen, Caen, France

⁵ INFN, Laboratori Nazionali del Sud, Catania, Italy

Abstract

The fragmentation of quasi-projectiles from the nuclear reaction $^{40}\text{Ca}+^{12}\text{C}$ at 25 MeV/nucleon was used to produce α -emission sources. From a careful selection of these sources provided by a complete detection and from comparisons with models of sequential and simultaneous decays, strong indications in favour of α -particle clustering in excited ^{16}O , ^{20}Ne and ^{24}Mg are reported.

1 Introduction

Clustering is a generic phenomenon which can appear in homogeneous matter when density decreases; the formation of galaxies as well as the disintegration of hot dilute heavy nuclei into lighter nuclei are extreme examples occurring in nature. As far as nuclear physics is concerned, the nucleus viewed as a collection of α -particles was very early discussed and in the last forty years both theoretical and experimental efforts were devoted to clustering phenomena in nuclei. Very recently the formation of α -particle clustering from excited expanding self-conjugate nuclei was revealed in two different constrained self consistent mean field calculations [1, 2]. The aim

of the present work was to obtain, from the experimental side, some information on α -particle clustering from excited and consequently expanding alpha-conjugate nuclei. The chosen experimental strategy was to use the reaction $^{40}\text{Ca}+^{12}\text{C}$ at an incident energy (25 MeV per nucleon) sufficient to possibly produce some hot expanding reaction products, associated with a high granularity-high solid angle particle array (to precisely reconstruct directions of velocity vectors). Then, by selecting the appropriate reaction mechanism and specific events the required information was derived.

2 Experimental details and event selection

The experiment was performed at INFN, Laboratori Nazionali del Sud in Catania, Italy. The beam impinging on a thin carbon target ($320\text{ }\mu\text{g}/\text{cm}^2$) was delivered by the Superconducting Cyclotron and the charged reaction products were detected by the CHIMERA 4π multi-detector [3]. The beam intensity was kept around 10^7 ions/s to avoid pile-up events. CHIMERA consists of 1192 telescopes (ΔE silicon detectors 200-300 μm thick and CsI(Tl) stopping detectors) mounted on 35 rings covering 94% of the solid angle, with very high granularity at forward angles. Details on A and Z identifications and on the quality of energy calibrations can be found in refs. [3, 4, 5]. Energy resolution was better than 1% for silicon detectors and varies between 1.0 and 2.5% for alpha particles stopped in CsI(Tl) crystals.

As a first step in our event selection procedure, we want to exclude from the data sample poorly-measured events. Without making any hypothesis about the physics of the studied reaction one can measure the total detected charge Z_{tot} (neutrons are not measured). In relation with their cross-sections and with the geometrical efficiency of CHIMERA, the well detected reaction mechanisms correspond to projectile fragmentation (PF) [6, 7, 8] with $Z_{tot}=19-20$ (target fragmentation not detected) and to incomplete/complete fusion with $Z_{tot}=21-26$. At this stage we can have a first indication on the multiplicity of α -particles, M_α , emitted per event for well detected events ($Z_{tot} \geq 19$ - see fig.1). M_α extends up to thirteen, which means a deexcitation of the total system into α -particles only. Moreover a reasonable number of events exhibit M_α values up to about 6.

The goal is now to tentatively isolate, in events, reaction products emitting α -particles only. To do this, knowing that at such incident energy ^{40}Ca as ^{20}Ne PF is dominated by alpha-conjugate products [6], we restrict our selection to completely detected PF events ($Z_{tot}=20$) composed of one pro-

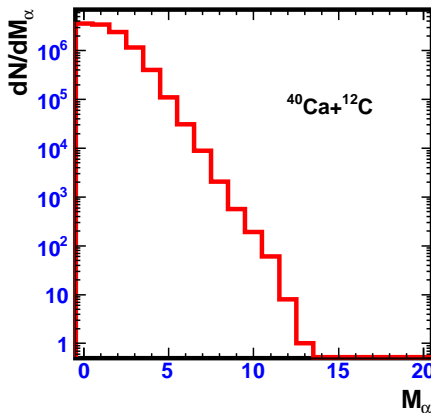


Figure 1: Distribution of α -particle multiplicity, M_α , for well detected events ($Z_{tot} \geq 19$)

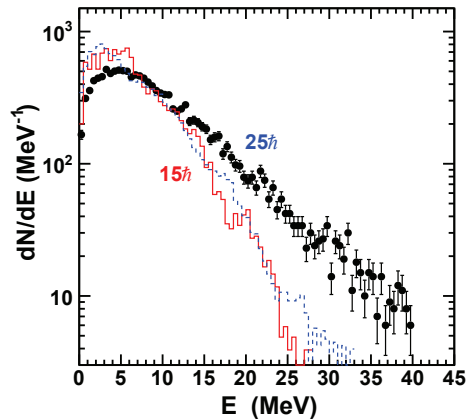


Figure 2: Sequential decay of excited Ca projectiles: energy spectra (in the $N\alpha=5$ system reference frame) of evaporated α -particles associated to a ^{20}Ne evaporation residue. Full points are experimental data and histograms are results of GEMINI simulations (see text)

jectile fragment and of four to six α -particles. Charge conservation imposes $Z_{frag}=20 - 2M_\alpha$.

After this double selection, the question is: from which emission source are the α -particles emitted? Several possibilities have to be considered and complementary selections must be done before restricting our study to alpha-sources emitting exclusively the M_α observed (called $N\alpha$ sources in what follows). Possibilities associated to selected PF events are the following:

I) considering the incident energy of the reaction and the strong forward focusing of reaction products, it is important to identify the possible presence of preequilibrium (PE) α -particles in our selected PF events. With the hypothesis that all the α -particles are emitted from their centre-of-mass reference frame, we noted a thermal distribution with the presence of a high energy tail starting at 40 MeV, which signs PE emission. Events in which such PE emission was possibly present were suppressed to prevent errors on alpha emitter properties; an upper energy limit was imposed to the α -particle energy, with a value of 40 MeV irrespective of M_α .

II) α -particles can be emitted from deexcitation of PF events via unbound states of ^{12}C , ^{16}O , ^{20}Ne and not directly from excited expanding $N\alpha$ sources. Multi-particle correlation functions [9, 5] were used to identify

unbound states 100% α -particle emitters and suppress a small percentage of events (1.6-3.6%).

III) it must be verified that the fragments associated with M_α are not the evaporation residues of excited Ca projectiles emitting only α -particles.

As far as the two first items are concerned the effect was to suppress from 8.5 ($M_\alpha=4$) to 12.8% ($M_\alpha=6$) of previously selected events. The last item will be discussed in the following section.

To conclude on this part, one can also indicate that if excited $N\alpha$ sources have been formed their excitation energy thresholds for total deexcitation into α -particles vary from 20 to 50 MeV when $N\alpha$ moves from 4 to 6. Their mean excitation energy per nucleon is rather constant around 3.3-3.5 MeV which indicates that average lowest densities around 0.7 the normal density may have been reached due to thermal pressure [10, 11].

3 Evidence for α -particle clustering

Before discussing different possible deexcitations of Ca projectiles and $N\alpha$ sources, information on the selected reaction mechanism is needed. Major features of PF events are reproduced by a model of stochastic transfers [8]. For primary events with $Z_{tot}=20$ excitation energy extends up to about 200 MeV, which allows the large excitation energy domain (20-150 MeV) measured for $N\alpha$ sources when associated to a single fragment; angular momenta extend up to $24 \hbar$, which gives an upper spin limit for Ca projectiles or $N\alpha$ sources.

Are α -particles emitted sequentially or simultaneously? To answer the question α -energy spectra are compared to simulations. For excited Ca projectiles and $N\alpha$ sources, experimental velocity and excitation energy distributions and distributions for spins are used as inputs. Then, results of simulations are filtered by the multi-detector replica. Simulated spectra are normalized to the area of experimental spectra.

For sequential emission the GEMINI++ code [12] was used. Before discussing $N\alpha$ sources, as said before, we must consider the possible evaporation from Ca projectiles. Excitation energy for projectiles is deduced from $E^*=E^*(N\alpha)+E_{rel}+Q$. E_{rel} is the relative energy between the $N\alpha$ source and the associated fragment (evaporation residue). Fig. 2 displays results of simulations with reconstructed excitation energy distribution for ^{40}Ca ($\langle E^* \rangle=88.2$ MeV) and gaussian distributions centred at 15 and $25\hbar$ for spins (RMS= $1.5\hbar$) as inputs; note that no more ^{20}Ne residues are produced for spin distributions centred at values larger than $25\hbar$. Comparison with

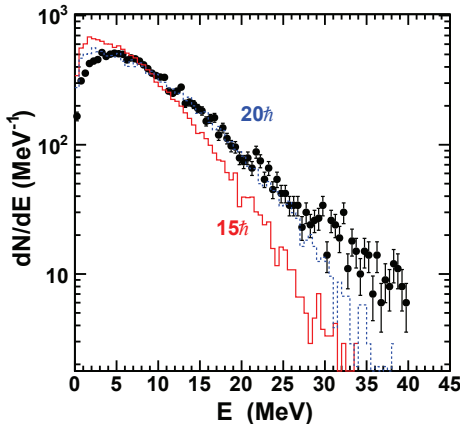


Figure 3: Decay of excited ^{20}Ne ($N\alpha=5$): α -particle energy spectra; full points are experimental data and histograms correspond to GEMINI simulations (see text).

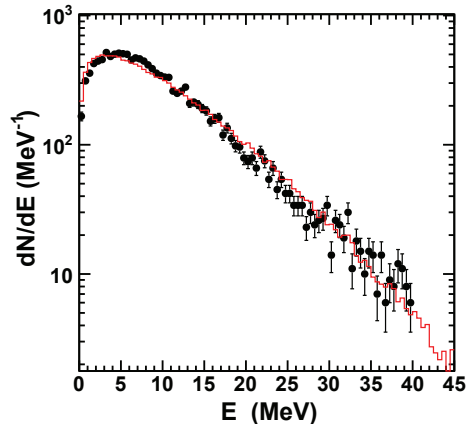


Figure 4: same as fig. 3 but histogram corresponds to a simulation of a simultaneous decay (see text).

experimental data shows a rather poor agreement indicating that such an hypothesis seems not correct. Same kind of results are observed for $N\alpha$ equal 4 and 6.

Considering now excited $N\alpha$ sources only, histograms in fig. 3 are examples of GEMINI simulation results for $N\alpha=5$. Gaussian distributions for spins are used as inputs and the best agreement with data is obtained with $\text{RMS}=1.5\hbar$ for spin distributions. The agreement between data and simulations appears poorer and poorer when $N\alpha$ value decreases. Moreover an important disagreement between data and simulations is observed for the percentages of $N\alpha$ sources which deexcite via ^8Be emission [13].

For simultaneous emission from $N\alpha$ sources, a simulation was done which mimics a situation in which α clusters are early formed when the source is expanding [1, 2] due to thermal pressure. The $N\alpha$ source is first splitted into α 's. Then the remaining available energy ($E^* + Q$) is directly randomly shared among the α -particles such as to conserve energy and linear momentum. Histogram in fig. 4 is the result of such a simulation, which shows a good agreement with data. Such agreement is also observed for $N\alpha$ equal 4 and 6. Similar histograms (within a few percents) were also obtained with simulations containing an intermediate freeze-out volume stage and then propagation in the Coulomb field.

4 Conclusions

In conclusion, the reaction $^{40}\text{Ca}+^{12}\text{C}$ at 25 MeV/nucleon bombarding energy was used to produce and carefully select minor classes of events from which excited $N\alpha$ sources can be unambiguously identified. Their excitation energy distributions are derived with mean values around 3.4 MeV per nucleon, which indicates that mean densities about 0.7 the normal density may have been reached. Their energetic emission properties were compared with two simulations, one involving sequential decays and a second for simultaneous decay. For excited expanding $N\alpha$ sources composed of 4, 5 and 6 α -particles, for which statistics is good enough for conclusive comparisons with simulations, evidence in favour of simultaneous emission (α -particle clustering) is reported.

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